Correlations between the shear wave velocity profile and the response spectrum based on SASW tests

Corrélation entre le profil de vitesse d'ondes de coupe et le spectre de réponse basé sur l'essai SASW

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ABSTRACT: This work analyses the seismic response of six sites, where seismic stations were located, during the 2010 Maule earthquake (Chile), correlating the ground acceleration response with the shear wave velocity profile and the parameter Vs30. In order to obtain the shear wave velocity profile, the SASW method was implemented, reaching a depth of 30 m. Trial tests were conducted where shear wave velocity profiles were already measured with Downhole tests. The results showed reasonable agreement between the velocity profiles. The obtained shear wave velocity profiles in most of the sites are consistent with the geology and stratigraphic information. The main conclusions of this work are that i) in soils with a shear wave velocity profile that does not increases monotonically with depth, the acceleration response spectrum presents more than one peak, which should be incorporated in the design spectrum with a wider plateau to cover all the peaks ; ii) no unique correlation was observed in all the sites between the Vs30 and the pseudo acceleration, which implies that this parameter is not sufficient by itself to seismically classify the soils, in particular if they have different geological formations.

RÉSUMÉ : Ce travail analyse la réponse sismique de 6 stations sismographe pendant le sisme du Chili du Maule dans l'année 2010, en reliant l'accélération de réponse en surface avec le profil de vitesse d' ondes de coupe et le paramétre VS30 pour chaque emplacement. Pour obtenir le profil de vitesse des ondes de coupe, la méthode SASW a étée mise en oeuvre jusqu'á des profondeurs au moins de 30 m. Des essais d'épreuve ont été effectués dans des emplacements où on avait préalablement mesuré la vitesse d'ondes de coupe á travers l'essai Downhole, en montrant les résultats un accord raisonnable entre les profils. Les principales conclusions de ce travail sont: i) Dans des sols avec un profil de vitesse d'ondes de coupe non monotonement croissant en profondeur, le spectre d'ondes de coupe d'accélération présente plus de un peak, lequel pourrait être intégré dans le spectre design vers d'un plateau plus large qui obtient couvrir tous les peaks; ii) Il n'y a pas été observée une seule corrélation dans tous les emplacements mesurés entre la VS30 et le spectre de réponse de pseudo-accélération, ce qui implique que ce paramètre n'est pas suffisant par elle seulement pour classer sismiquement le sol.

KEYWORDS: shear wave velocity, Vs30, SASW, response spectrum.

1 INTRODUCTION.

The 27th of February of 2010 the 8.8 Maule earthquake hit the central-south region of Chile, causing hundreds of deaths. Even though most of the casualties were caused by the tsunami that hit the coast along hundreds of kilometers, damage to relatively new buildings opened a debate about the way the Chilean seismic code was facing some important issues. One of these issues was related to the soil classification system. Before this earthquake, the most important parameter to classify seismically the soil was the Nspt. However, after the debate, the Vs30 took place as the most important parameter to seismically classify the soil. This change, along with other modifications, was implemented in the Chilean seismic code.

This article presents the main results of the work conducted by the authors, in order to analyze if the shear wave velocity profile up to a depth of 30 m and the Vs30 are good parameters to classify the soil.

In Chile the main methods to measure or estimate the shear wave velocity profiles were the Downhole, Crosshole and Refraction tests. The first two methods are relatively expensive and are time consuming, since they require one or more than one drillholes, respectively. The refraction test, on the other hand, measures the compressional wave velocity. Besides, this technique does not work if the shear wave velocity decreases with depth. Therefore, the SASW appeared as a fast and inexpensive method to estimate shear wave velocity profiles, taking into account that the Vs30 parameter is now much more required than in the past.

The SASW method was implemented to obtain shear wave velocity profiles up to a depth of at least 30 m in six sites where seismic stations recorded the Maule earthquake. The seismic response of these sites, like acceleration response spectrum and peak ground acceleration, were analyzed and correlated to the shear wave velocity profile and the Vs30 parameter.

2 METHODOLOGY.

The SASW (Spectral Analysis of Surface Waves) method was initially implemented using a 10 kg hammer and a 63.5 kg steel mass, dropping it from a height of approximately 0.3 m, where a depth of 15 m was reached (Peredo 2011). In order to reach deeper layers and estimate the shear wave velocity up to a depth of at least 30 m and therefore estimate Vs30, beside the 10 kg hammer, the 63.5 kg steel mas was lifted up to a height of 4.5 m using a tripod (Pinilla 2012).

Each test consisted in the placement of two 4.5 Hz geophones, located on the ground surface, 2, 4, 8, 16, 24, 32 and

40 m apart, in order to obtain the corresponding dispersion curve of each site. The geophones were connected to a data acquisition system Geometric Geode, were the ground vibrations were simultaneously recorded. The 10 kg hammer was used for distances between geophones up to 16 m and the 63.5 kg weight was used for the longer distances. Figure 1 shows the setup instrumentation in one of the sites, where is possible to see a geophone and the tripod in the back.

Before the tests were carried on, two calibration tests were conducted in two sites where the shear wave velocity was already measured with Downhole tests. A good correlation was observed between the shear wave velocity profiles, taking into account that in both cases the shear wave velocity presented a decrease in the velocity at certain depths. The Vs30 obtained with both methods presented a difference of 5 and 16% in each case, which is considered a reasonable error.

The SASW method requires good interpretation of the recorded data to obtain a reasonable dispersion curve. Therefore, it is very important to consider that this method requires qualified and trained professionals.

Figure 1. SASW instrumentation setup in one of the sites.

3 RESULTS.

Table 1 presents the location of each seismic station where the tests were conducted and the corresponding Vs30 that was estimated through the SASW method.

Table 1. Locations where the SASW method were conducted and corresponding Vs30.

Station	*Latitude (°)*	*Longitude (°)*	*V_{S30} (m/s)*
Peñalolén	-33.50	-70.58	337
Puente Alto	-33.58	-70.58	510
Mirador	-33.44	-70.65	583
Antumapu	-33.57	-70.63	441
Curicó	-34.98	-71.24	447
Hualañé	-34.75	-71.80	505

Figure 2 shows the estimated shear wave velocity profile in Peñalolén, Mirador and Curicó, sites where the shear wave velocity increased monotonically with depth. The Peñalolén and Mirador sites are located in Santiago. The Curicó site is located in the hospital of Curicó, located in the VII region, south of

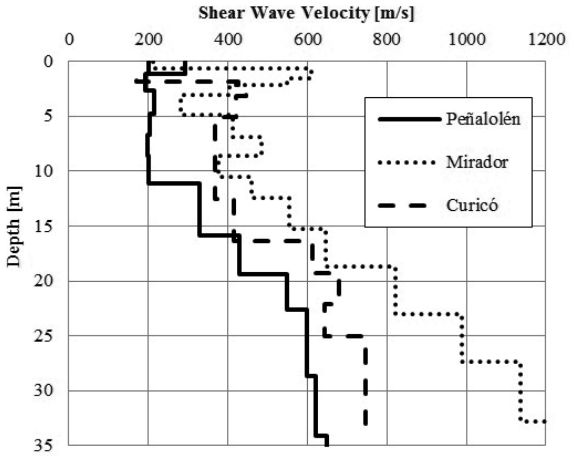

Figure 2. Shear wave velocity profile, velocity increasing monotonically with depth.

Santiago. These sites area located on gravely soils associated to fluvial deposits.

Figure 3 shows the estimated shear wave velocity profile in Puente Alto, Antumapu and Hualañé, sites where the shear wave velocity does not increases monotonically. Puente Alto and Antumapu sites are located in Santiago, and their soils correspond to gravelly deposits. Hualañé site is located in the hospital of Hualañé, in the VII region. It is expected that the soil in this area corresponds to granular soils with layers associated to colluvial deposits. In these three sites the velocity profiles indicate the existence of less rigid layers in between.

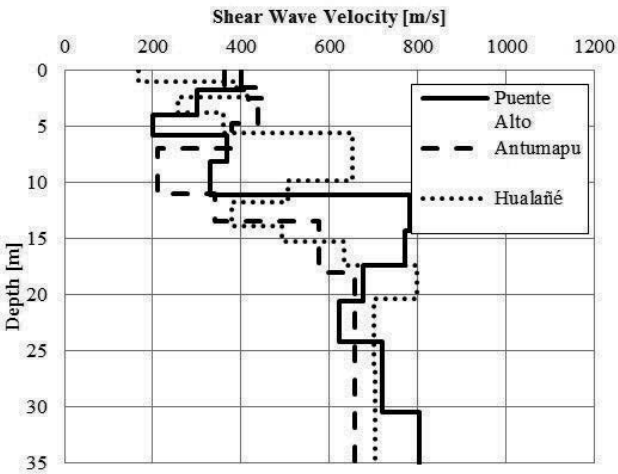

Figure 3. Shear wave velocity profile, velocity not increasing monotonically with depth.

4 ANALYSES.

Table 2 shows the predominant period and maximum pseudo acceleration of the response spectrum associated to the six sites analyzed.

Figure 4 shows the response spectrum (Boroschek 2010) associated to the three sites that present a shear wave velocity increasing monotonically with depth, Peñalolén, Mirador and Curicó. These sites present acceleration response spectrums with a clearly defined peak in a small range of periods. Beyond these periods, the pseudo acceleration decreases consistently with the period.

Table 2. Predominant period and maximum pseudo acceleration.

Station	*Predominant period (s)*	*Max Pseudo-acceleration (g)*
Peñalolén	0.33	1.23
Puente Alto	0.28	0.91
Mirador	0.23	0.64
Antumapu	0.2	1.06
Hualañé	0.15	1.92
Curicó	0.25	1.68

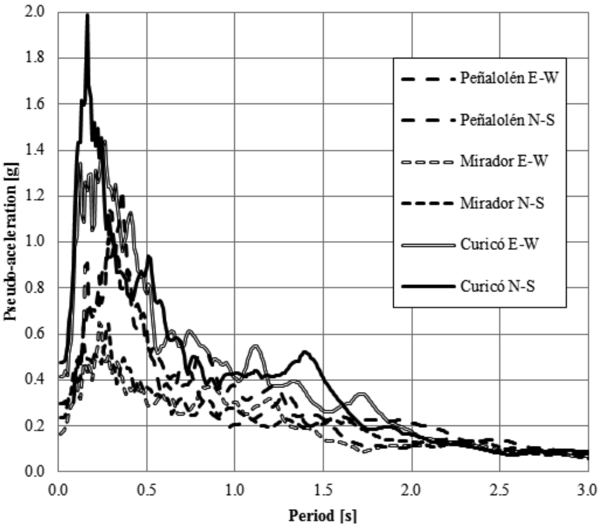

Figure 4. Acceleration response spectrum of the sites that present a shear wave profile increasing monotonically with depth.

Figure 5 shows the response spectrum (Boroschek 2010) associated to the three sites that present a shear wave velocity that does not increases monotonically with depth, Puente Alto, Antumapu and Hualañé. In these sites the acceleration response spectrum presents more than one peak with large pseudo acceleration. This response is believed to be associated to the soil profile and the fact that less rigid layers are located at certain depths, based on the SASW results. This type of profiles should be responsible that the deposit does not present only one predominant period associated to the whole deposit, but more than one. This correlation indicates that soil deposits with shear wave velocity that increases and decreases with depth would require a wider plateau in its design response spectrum to take into account that there is more than one peak.

Figure 6 shows the pseudo acceleration versus Vs30. It is possible to observe that there is no clear correlation between the pseudo acceleration and Vs30. However, if only the sites located in Santiago, in places with a similar geological formation, are considered, it is possible to observe a very good correlation. In this case, the pseudo acceleration decreases when the parameter Vs30 increases, as expected. It is important to mention that all these sites are flat and no topographic amplification is expected.

Figure 7 shows the predominant period as a function of the parameter Vs30. It is possible to observe that there is no correlation between them. The period of a deposit depends on several variables, like the depth to the rock, the shear wave velocity profile up to the rock, among others. Therefore, this lack of correlation with the parameter Vs30, which depends only of the soil profile in the first 30 m, is actually expected.

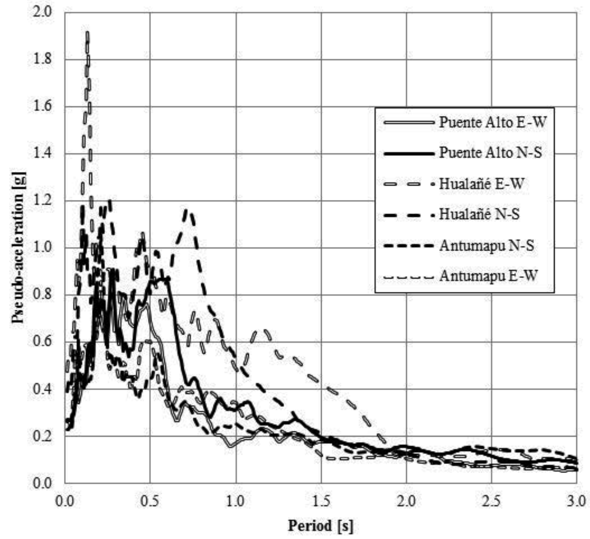

Figure 5. Acceleration response spectrum of the sites that present a shear wave profile not increasing monotonically with depth.

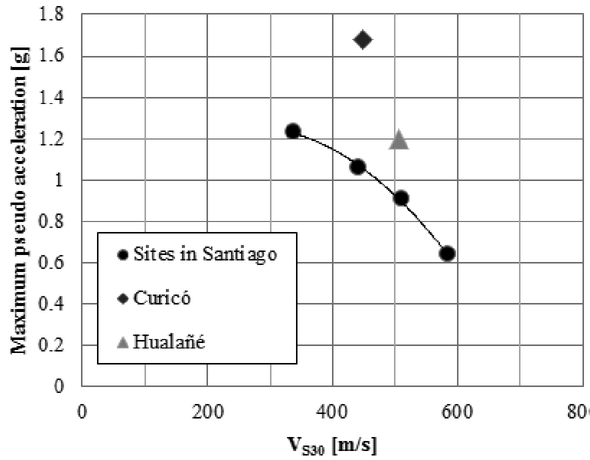

Figure 6. Pseudo acceleration versus Vs30.

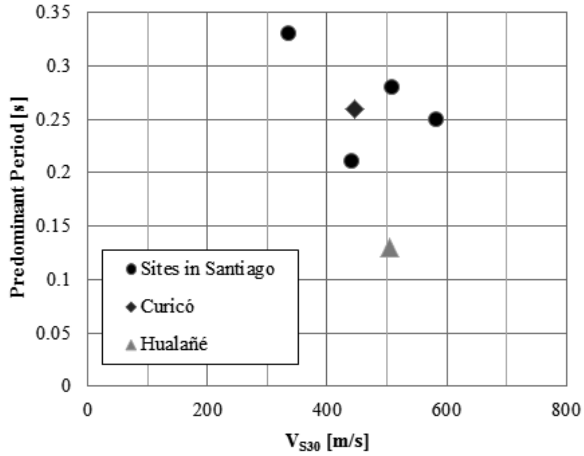

Figure 7. Predominant period versus Vs30.

5 CONCLUSIONS.

The main conclusions of this work are that:

The SASW method was successfully implemented to obtain shear wave velocity profiles up to 30 m depth. This method is able to capture reasonable well the shear wave velocity profile, even when it decreases with depth.

Vs30 obtained through SASW gives an error in the order of 15% compared to the one obtained through the Downhole technique.

The SASW method requires qualified and trained professionals, so they can be able to make a good interpretation of the recorded data and to obtain a reasonable dispersion curve. This is even more critical when the shear wave velocity decreases at a certain depth.

It is recommended to have stratigraphic information of the area in order to reduce even higher errors, associated with this methodology.

In soils with a shear wave velocity profile that does not increases monotonically with depth the acceleration response spectrum presents more than one peak, which should be incorporated in the design spectrum with a wider plateau to cover all the peaks.

A very good correlation was observed in the Santiago basin between the Vs30 and the pseudo acceleration, with the pseudo acceleration decreasing with an increment in the Vs30. This result would tend to support the use of Vs30 as a parameter for soil classification when the stiffness of the soil increases with depth.

However, no unique correlation was observed in all the sites between the Vs30 and the pseudo acceleration, which implies that this parameter is not sufficient by itself to seismically classify all the soils, in particular if they have different geological formations

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